A Novel Method for Enhancing the Passive Infrared Signature of Target Surrogates

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ABSTRACT

Concepts for the design and virtual prototyping of a full scale, signature engineered, threat vehicle surrogate for destructive testing are presented. Millimeter wave (MMW) and infrared (IR) signature prediction codes have been utilized in the design process as tools to evaluate a surrogate's signatures in a virtual environment prior to fabrication. Signature prediction codes have supplemented the surrogate design process through virtual prototyping of individual target components and total surrogate configurations; thereby shortening the total development time and final validation process of the surrogate target.

As part of the surrogate vehicle development effort, a method for fabricating a cost effective target surrogate with an accurate IR signature has been developed. This process uses sheet metal water tanks of a calculated thickness to emulate the heat capacity of thick metal armor. The water jackets have the same external shape and appearance of the threat armor it is meant to represent. The important difference is that the water tank can be manufactured from sheet metal and has a final weight and cost that is much less than the thick armor. Extensive experiments have shown that the surface temperatures of the water tanks closely matches the temperature of solid metal plates over the diurnal cycle for a variety of weather conditions.

The water tanks generate the appropriate passive infrared signature by having the same innate heat capacity as the corresponding threat vehicle component. With this technique thermal contrasts can be created between different vehicle components over changing weather conditions and the diurnal cycle. These contrasts are created automatically without any intervention from an operator or a control system. In addition to replacing thick armor with water jackets it is also possible to replace relatively expensive aluminum plates with thinner steel plates of equivalent heat capacity. Experimental results are presented that establish the effectiveness of this technique as well. The infrared signature enhancement techniques combined with the virtual prototyping process presented in this paper can greatly reduce the cost of producing a full scale target surrogate for live weapons testing.

INTRODUCTION TO TARGET SURROGATE VIRTUAL PROTOTYPING

One of the tasks of the Ground Targets System Engineering Division of the Targets Management Office (TMO), Project Manager for Instrumentation, Targets, and Threat Simulators (PM-ITTS), U.S. Army Simulation, Training and Instrumentation Command (STRICOM), is the development of ground targets for weapon system testing. Acquisition of targets and supporting services is driven by consumer needs. Depending on the weapon system's maturity and function to be demonstrated, consumers of targets may have a very specific need or may be uncertain of what they require. In all cases, TMO has to provide an affordable target that meets testing requirements. The increase in sophistication of weapon sensors has increased the level of detail required of the target, causing an increase in cost. Determining the minimum level of detail in a surrogate target design can decrease the cost of a target and simultaneously verify its suitability for weapon testing. This paper presents a virtual prototyping methodology by which this minimum level of detail can be ascertained.

The concept of virtual prototyping has gained a high degree of acceptance in recent years with the rapid increase of computing power and graphical visualization tools. It is now possible to easily simulate not just the form of a product design but its fit and function as well. This paper takes this concept a few steps further and discusses the use of MMW and IR signature prediction codes in the development of a design for a dual-mode target surrogate vehicle. The results of the signature predictions are then used with hardware-in-the-loop (HWIL) evaluations of the surrogate target signatures. The product of the current effort will not only be a partially pre-validated target surrogate design, but a process and infrastructure by which other target surrogates can be easily prototyped in the future.

The use and benefits of HWIL simulations in the evaluation of weapon system performance is well established throughout all branches of the Department of Defense. HWIL facilities provide a cost effective means of evaluation missile system performance to a level of fidelity not achievable with all-digital simulations. HWIL allows real-time, closed-loop performance evaluations of actual seeker hardware in a non-destructive manner. Thousands of simulated flights can be achieved with one seeker; in comparison to flight tests for which one flight results in the destruction of the unit under test. This is the first instance of utilizing this proven simulation technique for validating a surrogate target design instead of the munition. The advantages offered by this method include:

- signature designed surrogate
- level of detail considerations, knowing when the design is "good enough"
- design issues are resolved with simulations in a virtual environment
- design limitations can be quantified prior to fabrication

Although the target surrogate is intended to be a dual-mode IR/MMW target only IR virtual prototyping issues will be addressed here. The virtual prototyping of an IR target surrogate begins with the development of an IR signature of the threat vehicle the surrogate is meant to replicate. If thermal imagery of the threat vehicle exists with the corresponding meteorological data the thermal model can be developed to a high degree of fidelity. Figure 1 demonstrates this process. The top half of figure 1 shows the iterative design loop for the threat thermal model. The modeler starts with an appropriately grouped polygonal facet model translated into PRISM format. The model is run in PRISM with the applicable weather, terrain, and scenario files to generate a theoretical IR signature. The predicted signature is compared to the measured signature and modifications are then made to the model geometry or to the thermal or optical parameters of the model.

The bottom half of figure 1 demonstrates the surrogate IR signature design process. The threat thermal model design forms the foundation of the surrogate design. Since detailed physical parameters were required for the threat PRISM model the parameters are at hand for the surrogate design. In many cases the same materials and thickness' cannot be used to construct the surrogate and the threat thermal model will yield the information necessary for surrogate material augmentation. For example, if aluminum is used on the threat vehicle but the surrogate is to be made of steel or fiberglass, proper thicknesses, coatings, or augmentation can be more easily calculated from the data present in the thermal model.

INTRODUCTION TO TARGET SURROGATE PASSIVE INFRARED SIGNATURE ENHANCEMENT

The justifications for developing a surrogate vehicle passive infrared signature enhancement method are both technical and financial. It is critical not only to have a thermal signature of sufficient fidelity, but to have a surrogate vehicle that can be easily fabricated and maintained over the life of the testing program the surrogate was built for. The method for enhancing the infrared signature of surrogate vehicles involves the use of thin water tanks to match the heat capacity of thick metal parts of the threat vehicle. The water tanks are in the shape of the corresponding vehicle part and have the same external appearance.

There are many advantages of the water tank signature enhancement method. These include: low cost, ease of fabrication, ease of maintenance and repair, and no active control is required to maintain the proper signature over a wide range of weather conditions. The cost of the water tanks will be small as compared to thick plates, castings, or active temperature control. Water tanks can be constructed from thin sheet metal which is inexpensive and easily bent into complex shapes. Also, sheet metal is much more easily rolled and cut than thick metal plates. Creating a thermal surrogate of thick vehicle armor would normally require castings or inches thick metal plates. With water tanks, it is possible to create a thermal surrogate of these heavy and expensive components from thin sheet metal. The use of sheet metal has the additional advantage of enhanced maintainability in the field. If inert rounds are being used against the surrogate vehicle it is likely that the vehicle could suffer minor damage that

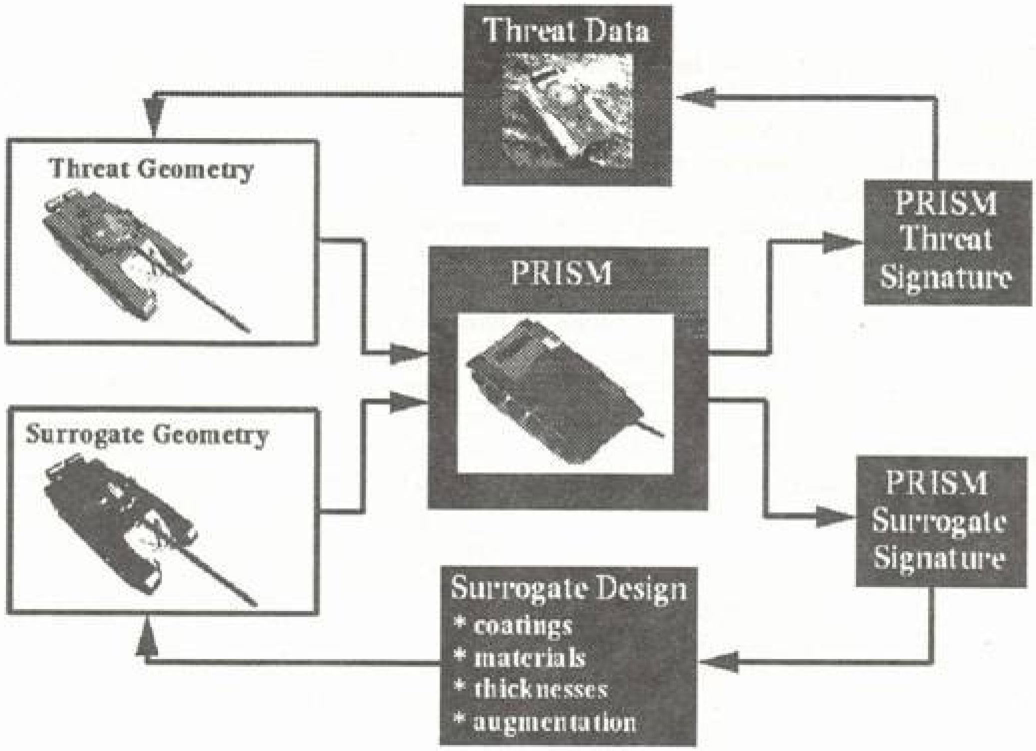

Figure 1. Target Surrogate IR Virtual Prototyping Process

would be detrimental to the surrogate signature but not the chassis. Most test ranges have the capability to work with sheet metal and make the minor repairs necessary to make the surrogate vehicle available for additional testing.

The critical parameter for this augmentation method is the thickness of the water tank. Since the length and width of the section have to remain the same the thickness will have to be calculated to yield an equivalent heat capacity of the appropriate volume of metal. While only water has been mentioned to this point it is important to note that any liquid could be used to fill the tanks.

BASIC ANALYSIS

The necessary volume can be determined from the explicit solution to the energy balance equation for a volume element. This states that the net energy rate into a volume element is equal to the heat stored and is expressed mathematically as:

$$\Sigma Q = M \cdot C_p \left[\frac{dT}{dt} \right] \tag{1}$$

where Q is heat rate, M is mass, C_p is specific heat, T is temperature, and t is time. Assuming that the heat rate is the same for the armor plate and the tank the MC_p product can be manipulated to achieve the same dT/dt which is the desired result.

For a water tank to have the same heat capacity as a metal plate the MC_p product must be equivalent. Expressed mathematically this is:

$$M_{armor} \cdot C_{p_{armor}} = M_{water} \cdot C_{p_{water}}. \tag{2}$$

Expressed as equivalent volumes:

$$Vol_{armor} \cdot \rho_{armor} \cdot C_{p_{armor}} = Vol_{water} \cdot \rho_{water} \cdot C_{p_{water}} \tag{3}$$

where Vol is volume and ρ is the density of the material. The desired result is an expression that indicates the fractional volume of water necessary to have the same heat capacity as an equivalent volume of armor. The above equation equates the heat capacities and rearranging the equation yields:

$$Vol_{water} = \left[\frac{\rho_{armor} \cdot C_{p_{armor}}}{\rho_{water} \cdot C_{p_{water}}} \right] \cdot Vol_{armor}. \tag{4}$$

The ratio of the products of the densities and specific heats yields the fractional volume of water required to have the same heat capacity as a volume of metal. Since the external dimensions of the armor plate must be identical this ratio is merely the ratio of the thicknesses.

Table 1 shows the approximate densities and specific heats for water, steel, and aluminum. These two metals were chosen as representative of the two types of material that might be replaced by water tanks on a surrogate. It is important to note that these values were chosen to represent a broad range of metal alloys and actual values used in fabrication may vary.

Table 1. Densities and Specific Heats

Material	Density (kg/m^3)	Specific Heat (kJ/kg°C)
water	1,000	4.2
steel	7,800	0.5
aluminum	2,700	0.9

Using the values of table one in the equation above yields the following numbers for the volume ratio of water necessary to replicate the heat capacity of a volume of steel or aluminum:

$$\text{steel:} \quad \tfrac{7800 \cdot 0.5}{1000 \cdot 4.2} = 0.93, \tag{5}$$

$$\text{aluminum:} \quad \tfrac{2700 \cdot 0.9}{1000 \cdot 4.2} = 0.58. \tag{6}$$

All of these calculations have assumed that the heat rate into (or out of) the volume element are the same for the armor plate and the water tank. The heat rate for a volume element can be expressed as:

$$Q = Q_r + Q_s + Q_k + Q_c + Q_p + Q_a, \tag{7}$$

where Q_r is longwave radiation exchange, Q_s is heat input from incident solar radiation, Q_k is convective heat transfer, Q_c is conductive heat transfer, Q_p is heat transfer due to precipitation/evaporation/condensation, and Q_a is any imposed heat from active vehicle components such as the engine, wheels, exhaust, etc.

At least four of the heat rate terms are effectively identical for the armor plate and the water tank. Solar radiation, convective, precipitation, and radiation exchange heat rates are the same as they have identical externally visible dimensions. The primary areas of difference will be in the conductive and active component heat terms since the water tanks are on a shell on a carrier chassis and are not parts of an actual threat vehicle. These two areas of difference cannot be avoided except by using the actual threat vehicle as a target. In addition, these concerns cannot be avoided by either thick metal plates on the surrogate shell or by water tanks on the surrogate shell. Hence, the relative ease of manufacture and small cost of using water tanks is a significant advantage of the water tank concept.

Another advantage of the water tank concept is a reduction in weight of the surrogate shell as compared to using thick plates for passive infrared signature augmentation. The equations for the mass of the water tank and armor plate are:

$$\text{water tank:} \quad M_{water} = \rho_{water} \cdot Vol_{water}, \tag{8}$$

$$\text{armor plate:} \quad M_{armor} = \rho_{armor} \cdot Vol_{armor}. \tag{9}$$

The equation describing the ratio of water mass to armor mass is:

$$\frac{M_{water}}{M_{armor}} = \frac{\rho_{water} \cdot Vol_{water}}{\rho_{armor} \cdot Vol_{armor}} = \frac{\rho_{water}}{\rho_{armor}} \cdot \frac{Vol_{water}}{Vol_{armor}}, \tag{10}$$

where the rightmost term, the ratio of volumes is simply the result of the previous derivation. Using the previously calculated ratios and the density values of table one yields:

$$\text{steel:} \quad \frac{M_{water}}{M_{steel}} = \frac{1000}{7800} \cdot 0.93 = 0.12, \tag{11}$$

$$\text{aluminum:} \quad \frac{M_{water}}{M_{alum}} = \frac{1000}{2700} \cdot 0.6 = 0.22. \tag{12}$$

These results indicate that the designer has approximately a factor of eight weight reduction when using water tanks to replace steel and a factor of approximately five when replacing aluminum.

TANK WALL THICKNESS ANALYSIS

The previous analysis is simplistic in that it assumes infinitesimal thickness of the sheet metal used to hold the water. Real water tanks will be made from sheet metal with finite thicknesses that can represent a significant percentage of the overall thickness of the water tank. For example, if a water tank surrogate is needed for a one inch thick aluminum plate the thickness of the tank from the previous analysis would be 0.58 inches. If the tank is constructed from 0.125 inch sheet aluminum almost half of the tank thickness will be aluminum instead of water. An analysis is required to determine the effects of this finite wall thickness on the heat capacity of the water tank. Figure 1 defines the pertinent dimensions and terms for the analysis.

As with the previous analysis, the imperfect thermal conduction between the aluminum and water will be ignored and the heat capacity of the aluminum and water will be calculated as a thermally homogeneous mass. Whereas the previous analysis dealt with finding the equivalent heat capacity of a volume of water this analysis will calculate the heat capacity of the water tank including the walls. Aluminum sheet metal will be the assumed tank wall material for this analysis.

The derivation begins with:

$$M_{armor} \cdot C_{p_{armor}} = M_{Tank} \cdot C_{p_{Tank}}. \qquad (13)$$

Since there are contributions to the heat capacity from both the water and the aluminum walls of the tank this equation must be rewritten as:

$$M_{armor} \cdot C_{p_{armor}} = M_{Al} \cdot C_{p_{Al}} + M_{water} \cdot C_{p_{water}}. \qquad (14)$$

Expressed as equivalent volumes:

$$Vol_{armor} \cdot \rho_{armor} \cdot C_{p_{armor}} = Vol_{Al} \cdot \rho_{Al} \cdot C_{p_{Al}} + Vol_{water} \cdot \rho_{water} \cdot C_{p_{water}} \qquad (15)$$

Replacing the volumes with the product of the area and thickness' and realizing that the area is the same for the water, aluminum, and armor and can be canceled yields:

$$d_{armor} \cdot \rho_{armor} \cdot C_{p_{armor}} = 2 \cdot d_{Al} \cdot \rho_{Al} \cdot C_{p_{Al}} + d_{water} \cdot \rho_{water} \cdot C_{p_{water}} \qquad (16)$$

In most cases the thicknesses of the walls of the tank can be set by available materials or standard sheet aluminum thicknesses. Once the wall thicknesses are set the only unknown remaining is the thickness of the water which can be easily solved for. The water thickness is given by:

$$d_{water} = \frac{d_{armor} \cdot \rho_{armor} \cdot C_{p_{armor}} - 2 \cdot d_{Al} \cdot \rho_{Al} \cdot C_{p_{Al}}}{\rho_{water} \cdot C_{p_{water}}}. \qquad (17)$$

With the water thickness calculated the external dimensions of the tank can be seen from figure 2 to be:

$$d_{Tank} = d_{water} + 2 \cdot d_{Al} \qquad (18)$$

The basic analysis showed that to create a water tank surrogate for a one inch thick aluminum armor plate a water tank with an external dimension of 0.58 inches is required. Assuming a tank wall thickness of 0.090 inches and using the values from table 1, the resulting water thickness is 0.46 inches for a total tank thickness of 0.64 inches. A surrogate for a three inch thick aluminum plate with 0.125 inch thick aluminum walls requires a water thickness of 1.59 inches for a total tank thickness of 1.84 inches. The basic analysis required a tank thickness of 1.74 inches. Both of these examples show that the wall thickness has a small yet measurable effect on the required overall thickness of the tank.

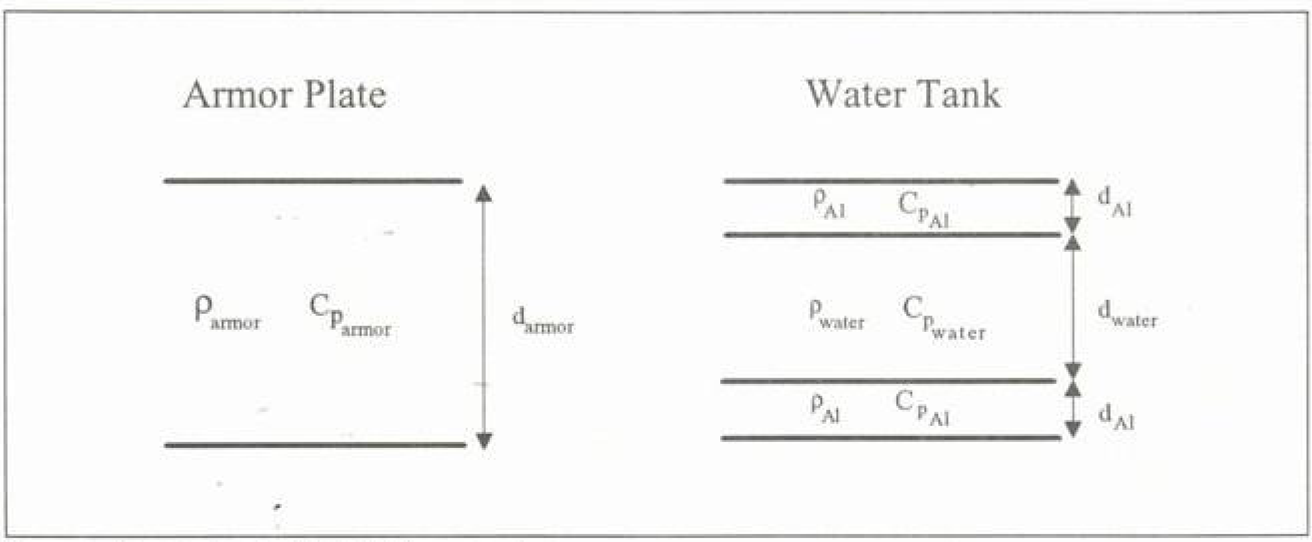

Figure 2. Terminology for Wall Thickness Analysis

SOLID PLATE ANALYSIS

It can be desirable to replace certain types of plate metals on the surrogate shell with less expensive or more easily machined thermally equivalent counterparts. To compare steel and aluminum the derivation begins with:

$$Vol_{steel} \cdot c_{p_{steel}} \cdot \rho_{steel} = Vol_{Al} \cdot c_{p_{Al}} \cdot \rho_{Al}. \quad (19)$$

Solving for the volume of steel necessary to replace an equivalent volume of aluminum yields:

$$Vol_{steel} = \frac{c_{p_{Al}} \cdot \rho_{Al}}{c_{p_{steel}} \cdot \rho_{steel}} \cdot Vol_{Al} = \frac{2700 \cdot 0.9}{7800 \cdot 0.5} \cdot Vol_{Al} = 0.62 \cdot Vol_{Al}. \quad (20)$$

This result is somewhat intuitive in that steel, while having about half the specific heat of aluminum, has almost three times the density. Therefore a given volume of steel has over one and a half times the heat capacity of an identical volume of aluminum. An example of this using standard metal thicknesses is five-eighths inch aluminum and three-eights inch steel. The three-eighths steel is potentially easier to work with and definitely less expensive. These two thicknesses of these two metals were used in the experiments described later in this report.

COLD TEMPERATURE ISSUES

Unlike the metal that the water is meant to replace, water can undergo phase changes over common terrestrial temperature spans. The latent heat of the water can cause errors as the temperature passes through the freezing point. As the temperature of the plate and tank cools off the temperature of the water tank will lag behind the temperature of the plate when the temperature passes through the freezing point of water. A plateau is formed in the temperature versus time profile due to the evolution of the latent heat of fusion.

There is an obvious cause for concern if the water tank augmentation method is to be used in cold weather. Large errors would occur as the temperature passed through the freezing point. The temperature of the solid aluminum plate would continue to change while the temperature of the water tank would lag behind both on the cooling and the heating cycles. The latent heat of fusion must be added or removed from the water before the temperature can change.

Some type of antifreeze must be combined with the liquid to avoid this error during cold weather operations. If the freezing point of the liquid in the tanks can be lowered, the weather conditions under which the vehicle can operate can be extended. When the freezing point of the fluid in the tanks is beneath the lowest expected air temperature the water tank temperature can be expected to behave appropriately. For this reason it was decided to use an ethylene glycol/water mixture in the water tanks used in this series of experiments.

EXPERIMENTAL CONFIGURATION

A series of experiments were completed to verify the water tank infrared signature augmentation concept. The experiments were conducted by the Component Test and Surveillance Branch of the Redstone Technical Test Center (RTTC) at building 4500 on Redstone Arsenal. A total of ten test items were used in two series of experiments. Table 2 lists the items used in the experiment.

Table 2. Experimental Test Item Descriptions

Test Item	Height	Width	Thickness	Material
3 in. al. plate	36 in.	36 in.	3 in.	solid al.
3 in. surr. #1	36 in.	36 in.	2.1 in.	0.090 in. al.
3 in. surr. #2	36 in.	36 in.	2.0 in.	0.090 in. steel
1 in. al. plate	22 in.	22 in.	1 in.	solid al.
1 in. surr. #1	22 in.	22 in.	0.75 in.	0.090 in. al.
1 in. surr. #2	22 in.	22 in.	0.66 in.	0.090 in. steel
5/8 in. al. plate	22 in.	22 in.	0.625 in.	0.625 in. al.
3/8 in. steel plate	22 in.	22 in.	0.375 in.	0.375 in. steel
al. sheet	36 in.	36 in.	0.125 in.	0.125 in. al.

The first series of experiments took place in late November and early December while the second series took place in late March, April and early May. All test items were placed on top of thick wooden blocks in a grassy area approximately 20 feet from the rear of the building housing the data collection system. A typical setup is shown in figure 3. There were two J-type thermocouples attached with dental cement to the front surface of each test item. All thermocouples were connected to a Beckman Industrial Model 245, twenty channel data logger. The data logger was set to record the thermocouple temperatures at fifteen or thirty minute intervals.

Over the course of the experiments the orientation of the test items was changed and additional test items were added. Freezing temperatures were encountered in the first series of experiments which resulted in a fifty/fifty mixture of ethylene glycol and water being used in the tanks in the second experiment. All test items were

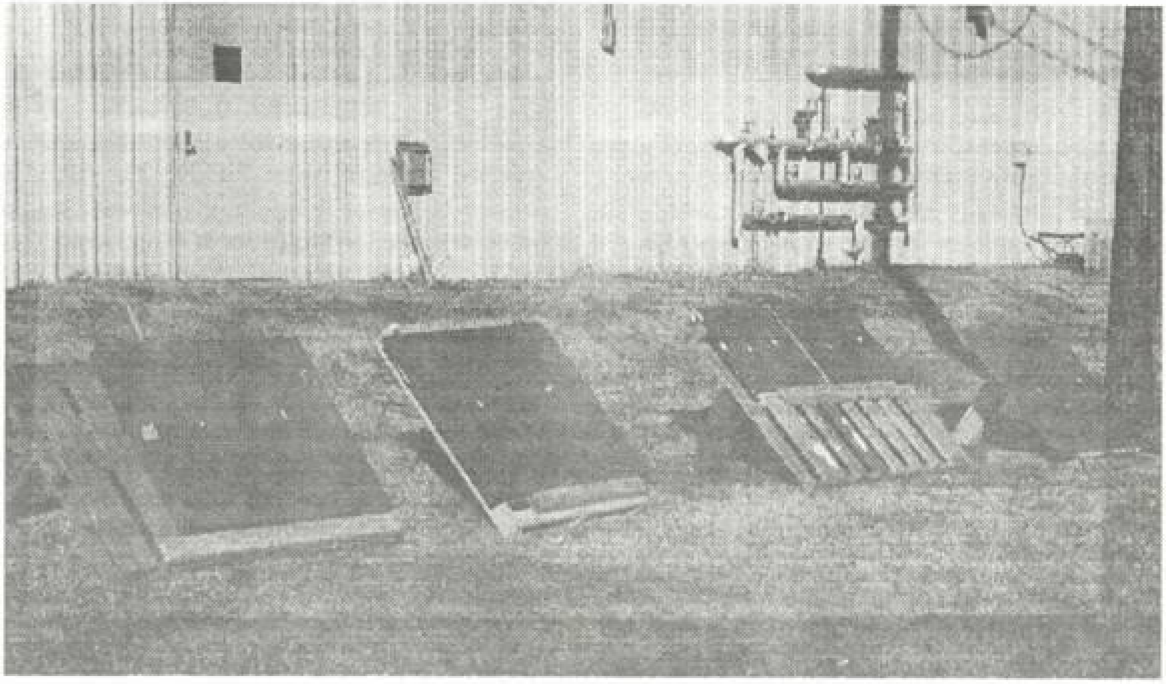

Figure 3. Typical Experimental Setup

painted with a dark green epoxy paint on their top surfaces and sides.

EXPERIMENTAL RESULTS

Results from selected experiments will be shown and discussed. The two series of experiments can be divided into fourteen data collections of varying length. Particular data collections will be discussed that demonstrate important operational parameters of the water tank concept.

Figure 4 shows the data collected from the first data collection. The items used in this test were the thin aluminum sheet, the three inch aluminum plate and its water filled surrogate and the one inch aluminum plate and its water filled surrogate. The items were lying flat on wooden blocks. The data was collected from 11:30 AM on November 18, 1994 to 9:00 AM on November 21, 1994. The weather was clear and calm on the first full day and during the morning of the 19th with clouds and windy conditions starting around noon on the 20th. The test items were stored inside prior to the test which explains their nearly identical temperatures at the start of the data collection. The data shows that the surface temperatures of the metal plates and their surrogates match very closely over the entire diurnal cycle. While it is difficult to see in the figure the time of greatest error is in the late morning when the surface temperature of the three inch plate and its surrogate are approximately three degrees apart.

Figure 5 shows selected data collected from the third data collection. The data was collected from 9:00 AM on December 1, 1994 to 3:30 PM on December 2, 1994. This figure demonstrates the importance of using a fluid in the tanks that has a lower freezing point than the lowest expected temperature for a test. The only difference between the test setup of figure 5 and the test setup of the previous figure was that the test items were tilted at a 45 degree angle to the south for the data in figure 5. The data plotted in the figure is for the one inch aluminum plate and its water filled surrogate. Note that the temperatures start out almost thirty degrees apart, come together around noon and match almost exactly from noon into the evening. The data points of interest occur when the surface temperatures drop below freezing around 10:00 PM. The temperature of both of the surfaces drop below freezing for a short time but then the tank temperature suddenly increases up to the freezing point of water. This phenomena is known as recalescence. The tank temperature stays near the freezing point of water until well after sunrise, creating a large temperature error between the tank and the plate.

Figure 6 shows the effects of having different fluids in the tanks. For this data collection the plates were upright and facing west with their rear surfaces shaded with cardboard. The data was collected from 1:00 PM on April 4, 1995 to 11:00 AM on April 7, 1994. Due to the cold weather effects seen in the first series of experiments it was decided to use a 50/50 mixture of ethylene glycol and water in the second series of experiments. Initial data analysis showed inferior results during warm weather with the ethylene glycol mixture as compared to the water filled tanks so it was decided to include water filled tanks for a direct comparison under identical conditions. As can be seen in figure 6 the surface temperature of the water filled tank barely deviates from the surface temperature of the solid plate over the entire diurnal cycle. In contrast, the surface temperature of the ethylene glycol filled tank has a temperature error of as much as ten degrees. This is attributed to the ethylene glycol mix having a lower thermal conductivity as compared to water.

Figure 7 shows a comparison between solid steel and aluminum plates that were calculated as having equivalent heat capacities. The data in this figure was collected from 3:00 PM March 17, 1995 to 8:00 AM March 20, 1995. As can be seen in the figure the surface temperatures of the two plates are effectively identical over the entire data collection period.

CONCLUSIONS

This paper presented the concept of using infrared signature prediction codes to create a virtual prototype of an armored vehicle surrogate. The authors have found that this process is extremely beneficial to the successful creation of a target surrogate as one of the by-products of this process was the IR signature enhancement concept also presented in this paper. Building an IR signature model of the threat to be replicated has also proven to be essential to the target surrogate creation process.

The results of the experiments presented here indicate that the use of water tanks to enhance the infrared signature of a vehicle surrogate is a technically feasible approach. The data shows that the surface temperature of the water tanks is extremely close over a majority of the diurnal cycle. The largest errors in the experiment were during the periods of rapid temperature rise in the morning and early afternoons. Even during these periods of relatively large error there was still a significant thermal lag created with the water tanks which was the primary purpose of the experiment. The experimental results verify the basic concept of using components with equivalent heat capacities for surrogate vehicle construction. The method allows for the inclusion of passive thermal target features without a complex heating and cooling system or extremely heavy armor plating. The experiments also showed that water appears to be a better choice for a tank fluid over an ethylene glycol mixture which may be at least partially attributed to its higher thermal conductivity. What was not presented here was that the ethylene glycol mix worked well in cold weather but not as well in warm weather. This would indicate the use of plain water in the tanks for warm weather target surrogate deployments and an ethylene glycol mix for use in cold weather.

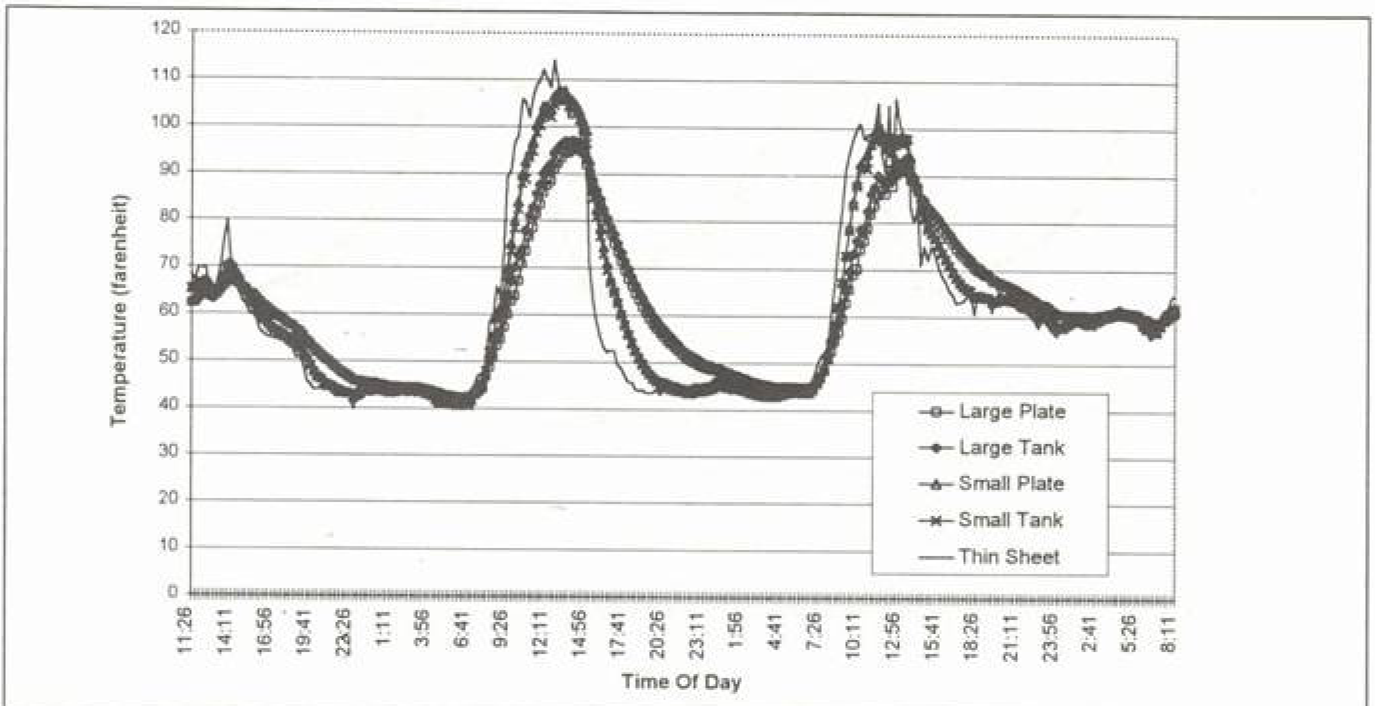

Figure 4. Experimental Results for Three Inch Plate, One Inch Plate and Their Water Tank Surrogates